#2045 THE INSTITUTE OF PAPER CHEMISTRY

Project Reports

PROJECT REPORT FORM

Copies to: ✓Files
Swanson
Kurath
Reading Copy

PROJECT NO. ✓ 2045
COOPERATOR IPC
REPORT NO. One
DATE June 30, 1958
NOTE BOOK 1694
PAGE 7 TO 98
SIGNED Sheldon Kurath
Sheldon Kurath

I. CONSTRUCTION OF A DOUBLE ELECTROMAGNETIC TRANSDUCER

II. PRELIMINARY INVESTIGATIONS ON THE DYNAMIC MECHANICAL PROPERTIES OF MATERIALS OF INTEREST TO THE PAPER INDUSTRY

I. CONSTRUCTION OF A DOUBLE ELECTROMAGNETIC TRANSDUCER

INTRODUCTION

The use of the double electromagnetic transducer is one of the most convenient means of studying the mechanical properties of materials. In the past, the transducer has been one of the more powerful tools in the field of experimental polymer physics. When used in conjunction with molecular and phenomenological theories of viscoelasticity it provides a convenient means of equating mechanical properties to molecular geometry and molecular packing. The transducer described in the following sections is similar to an instrument that was constructed and used in another laboratory (1). The instrument in use at the present time was constructed here at The Institute of Paper Chemistry (2). It is an instrument capable of measuring the dynamic shear modulus of materials in the 6 to 2500 c.p.s. frequency range.

SOME IMPORTANT PRINCIPLES

The material in this section is intended to aid in the understanding of the theory and operation of the electromagnetic transducer. It contains an introduction to viscoelasticity and some principles of electro-mechanical systems.

If a strain, $\epsilon = e^{j\omega t}$ is applied to a viscoelastic solid a stress, σ, will be observed which is out of phase with the strain, Figure 1. If the strain is represented by a vector in the complex plane, then the viscoelastic stress can be considered as a vector which precedes the strain. The stress vector can be decomposed into two components. The component in phase with the applied strain is characteristic of a Hookean solid. The stress on a Newtonian liquid is proportional to the rate of strain and therefore the viscoelastic stress in phase with the rate of strain vector, $\dot{\epsilon} = d\epsilon/dt$, is characteristic of a liquid.

By analogy with ordinary stress-strain relations, the modulus can be defined as the ratio of stress to strain. For a viscoelastic solid the modulus will be complex in nature. If the strain is a shear strain the modulus will be the complex shear modulus, $G^*(j\omega)$, and is given by,

$$\frac{\text{stress}}{\text{strain}} = G^*(j\omega) = G'(\omega) + j\,G''(\omega) \tag{1}$$

where $G'(\omega)$ is the real or solid component of the complex shear modulus and $G''(\omega)$ is the imaginary or liquid component. This means of representing the modulus has an advantage over the more commonly used static modulus in that it reveals solid and liquid behavior as components of the complex modulus.

The liquid nature of $G''(\omega)$ is easily seen by writing this as,

$$G''(\omega) = \omega\,\eta'(\omega) \tag{2}$$

where $\eta'(\omega)$ is the dynamic viscosity. Another useful relationship is the

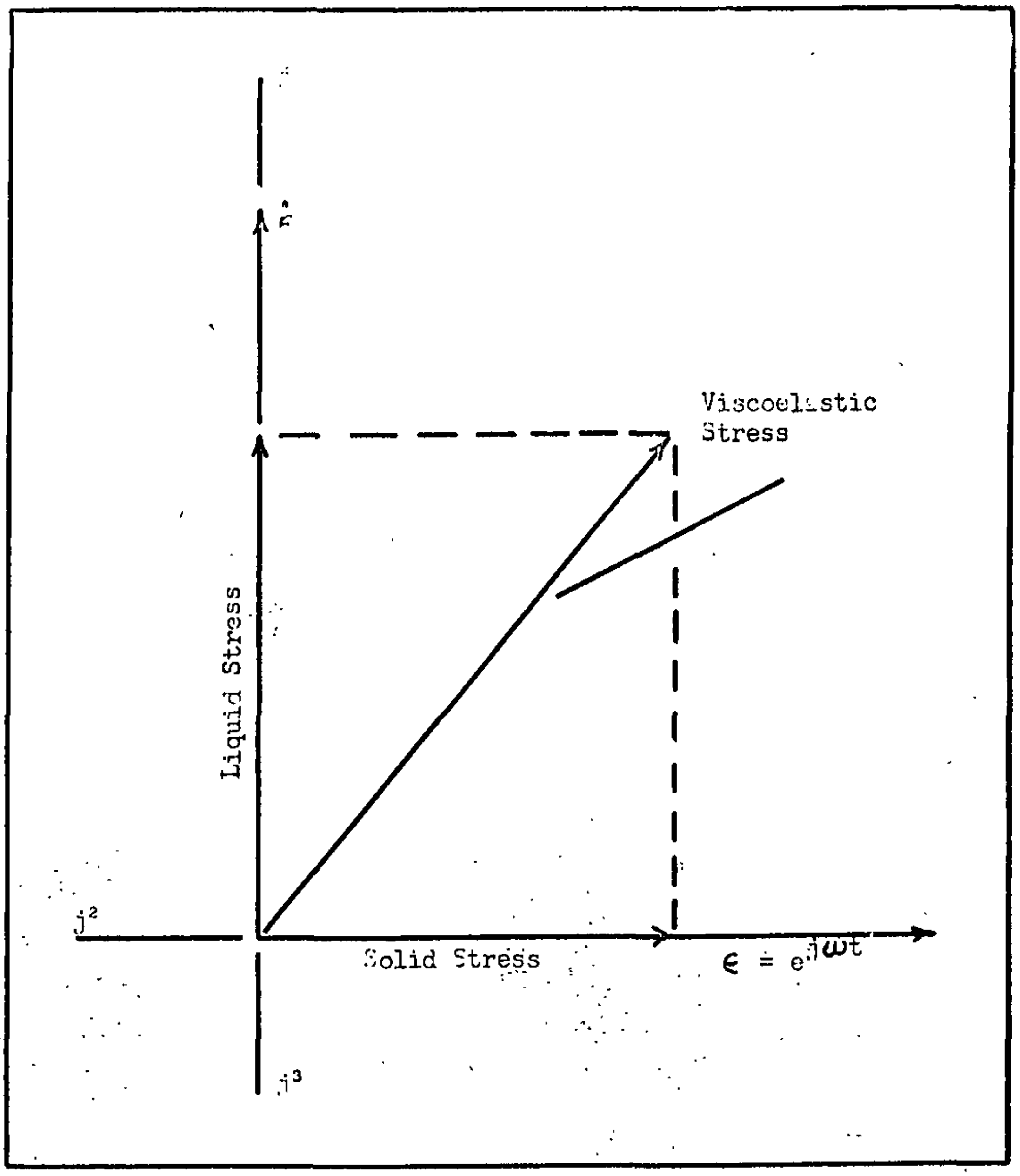


Figure 1. Stress-Strain Relations in the Complex Plane for a Viscoelastic Solid

mechanical loss tangent, $\tan\delta = G''(\omega)/G'(\omega)$, since it is related to energy stored and energy lost per cycle, i.e.,

$$\frac{\text{Energy lost/cycle}}{\text{Energy stored/cycle}} = \pi \frac{G''(\omega)}{G'(\omega)} \tag{3}$$

This is directly related to the resiliance of the material.

An alternate set of relations in common use are the compliance relations. The complex shear compliance, $J^*(j\omega)$, is the ratio of shear strain to stress and can be obtained from the complex shear modulus using the relation,

$$J^*(j\omega) = \frac{1}{G^*(j\omega)} = \frac{\text{strain}}{\text{stress}} \tag{4}$$

It is most easily obtained in component form,

$$J^*(j\omega) = \underset{\text{Solid}}{J'(\omega)} - j\underset{\text{Liquid}}{J''(\omega)} \tag{5}$$

by use of the relations

$$J'(\omega) = \frac{G'(\omega)}{[G'(\omega)]^2 + [G''(\omega)]^2} \tag{6}$$

and

$$J''(\omega) = \frac{G''(\omega)}{[G'(\omega)]^2 + [G''(\omega)]^2} \tag{7}$$

As in the case of the complex shear modulus, the shear compliance has solid and liquid properties.

In those media where the Boltzman superposition principle applies, the components of the complex shear modulus can be written as,

$$G'(\omega) = \int_0^\infty H(\tau) \frac{\omega^2 \tau^2}{1 + \omega^2 \tau^2} d\tau \tag{8}$$

and

$$G''(\omega) = \int_0^\infty H(\tau) \frac{\omega \tau}{1 + \omega^2 \tau^2} d\tau \tag{9}$$

where H (τ) is the relaxation distribution function and τ is the relaxation time. Mathematical techniques are available for recovering H (τ) from under the integral sign (3). If the Boltzman superposition principle applies the relaxation distribution function obtained from these two expressions will be identical. In addition the relaxation distribution function can then be used to compute the stress relaxation modulus through use of the relation,

$$G(t) = \int_0^\infty H(\tau)\, e^{-t/\tau}\, d\tau, \tag{10}$$

where t is the time.

The mechanical properties of many polymeric systems are extremely time dependent so that it is desirable to know $G^*(j\omega)$ over as wide a frequency range as possible.

The most satisfactory method of determining the complex shear modulus as a function of frequency is through the use of the electromagnetic transducer. The operation of the transducer is based on analogies that exist between electrical and mechanical systems. By making use of these analogies it is possible to convert mechanical quantities into their electrical counterparts and then carry out precise electrical measurements. In general this can be done with greater precision than can be obtained by purely mechanical means, (i.e. by the measurement of stress and strain). Once electrical measurements are obtained the complex shear modulus can be determined by direct computation.

The electrical and mechanical equivalents upon which the operation of the transducer is based are given in Table I. The impedance relations, $\vec{Z}$, are the most fundamental relations given. In a mechanical system impedance is the ratio of force $\vec{F}$ to velocity $\vec{V}$ while for an electrical system it is the ratio of voltage $\vec{E}$ to current $\vec{I}$. Both impedances are vector quantities and can be represented as vectors in the complex plane. The mass of a mechanical system and the inductance of an electrical system represent inertial quantities. Their corresponding impedances $\vec{Z}_m$ and $\vec{Z}_e$ are given in the table. Electrical energy can be stored in a capacitor and mechanical energy is stored in the deformation of a spring and therefore the role of the spring and capacitor are similar. Finally, energy may be dissipated in the resistance of an electrical circuit while the viscosity is the corresponding dissipation term in a mechanical system. These are the principles upon which the electromagnetic transducer operates. The use of these principles is discussed in the section on theory and operation.

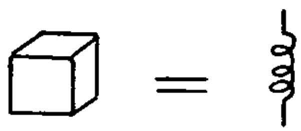
TABLE I

MECHANICAL AND ELECTRICAL ANALOGUES

MECHANICAL IMPEDANCE - ELECTRICAL IMPEDANCE

$\vec{Z}_m = \dfrac{\vec{F}}{\vec{v}}$ $\qquad$ $\vec{Z}_e = \dfrac{\vec{E}}{\vec{I}}$

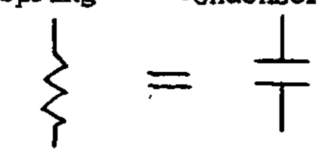
Mass - Inductance



m $\qquad$ L

$Z_m = j\omega m$ $\qquad$ $Z_e = j\omega L$

Spring - Condenser

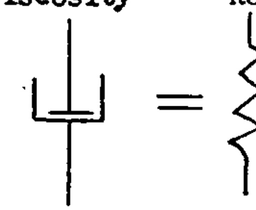


k $\qquad$ C

$Z_m = \dfrac{-jk}{\omega}$ $\qquad$ $Z_e = \dfrac{-j}{\omega C}$

Viscosity* - Resistor

η



R

$Z_m = \eta$ $\qquad$ $Z_e = R$

*The mechanical element represented here is a "dashpot" filled with a Newtonian liquid. It has viscous properties only.

Transducer Construction

The basic unit of the double transducer is a stiff tube suspended by means of 8 steel wires, see Figures 2 and 3. The central portion of the tube is constructed of aluminum (4) and is a hollow tube 4" X 13/16" with 1/32" walls. Magnesium (5) inserts are mounted at each end and serve to support two micarta (6) coil forms. The electric coils are double layers of #34 magnet wire (7) and are attached to the coil forms by means of coil varnish. The total weight of the assembled tube is 42.53 g.

Each electric coil is situated in the air gap of a permanent magnet, Figure 3. The tube is mounted so that it may translate freely in an axial direction. The pole faces of the magnets are specially shaped so as to supply the coils with a radial magnetic field. The magnet proper is a cast Alnico 5 ring magnet 4.101 "O.D X 2.994" I.D. X 2" long and has the direction of magnetization parallel to the length (8). The magnet was remagnetized before being used. The pole faces of the magnet were machined from an annealed bar of Armco ingot iron (9).

The use of this particular tube and magnet arrangement has definite electrical advantages. By using the specially shaped pole faces it is possible to eliminate coupling between the two coils of the tube. In addition the use of micarta coil forms eliminates the effects of eddy currents which would be encountered if the coil forms were made of aluminum.

The tube and magnets are mounted in a massive brass holder (10) which is shaped to accommodate the magnets. Sample pairs are strained sinusoidially in shear by pressing them between the flat faces of the tube and two massive brass blocks. The blocks are mounted on a grooved track and may be clamped in any position along the track. The position of the

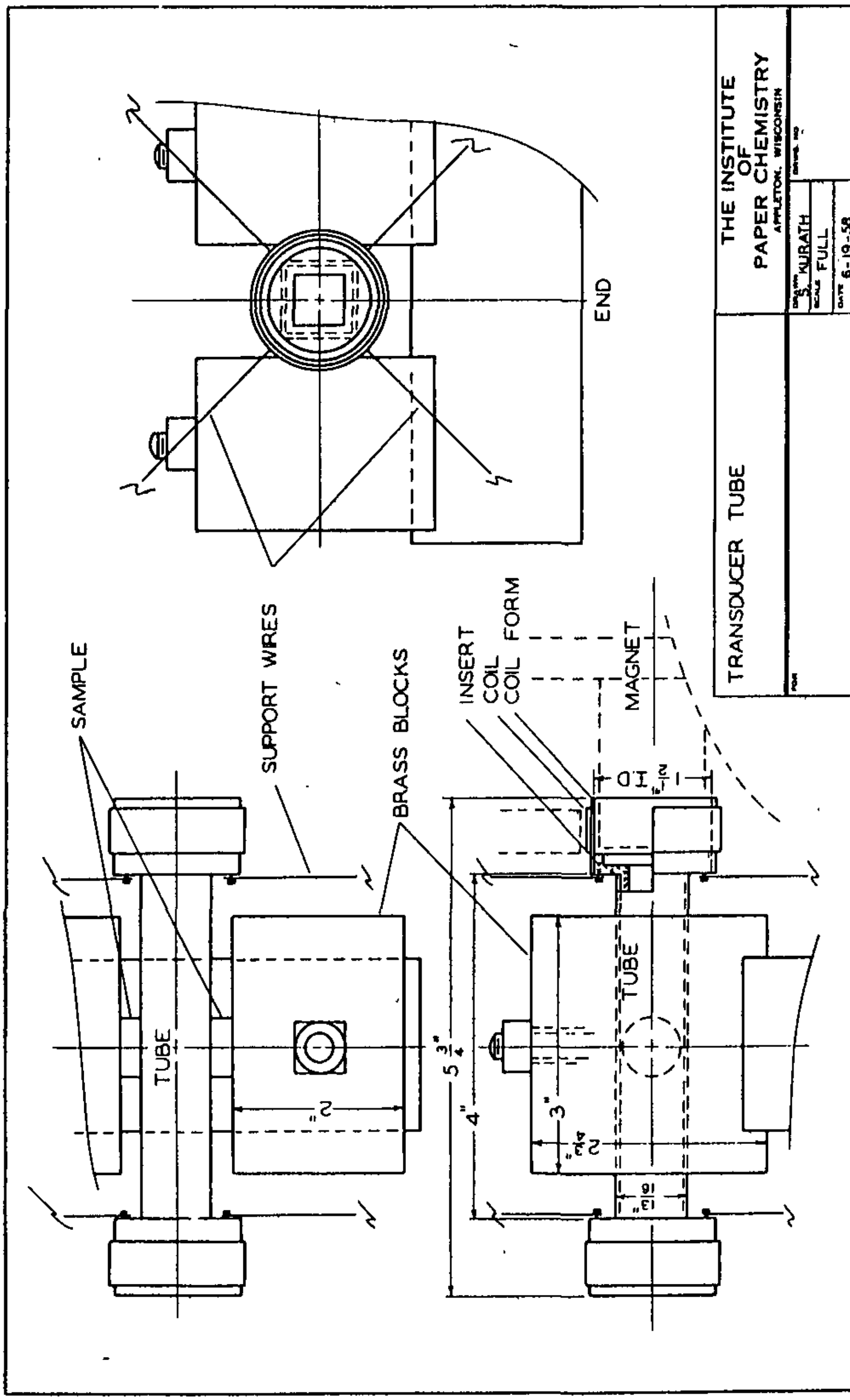

THE INSTITUTE OF PAPER CHEMISTRY
APPLETON, WISCONSIN
TRANSDUCER TUBE
S. KURATH
FULL
6-19-58
END
SAMPLE
SUPPORT WIRES
BRASS BLOCKS
INSERT
COIL
COIL FORM
MAGNET
TUBE
TUBE
2"
5 3/4
4"
3"

Figure 2

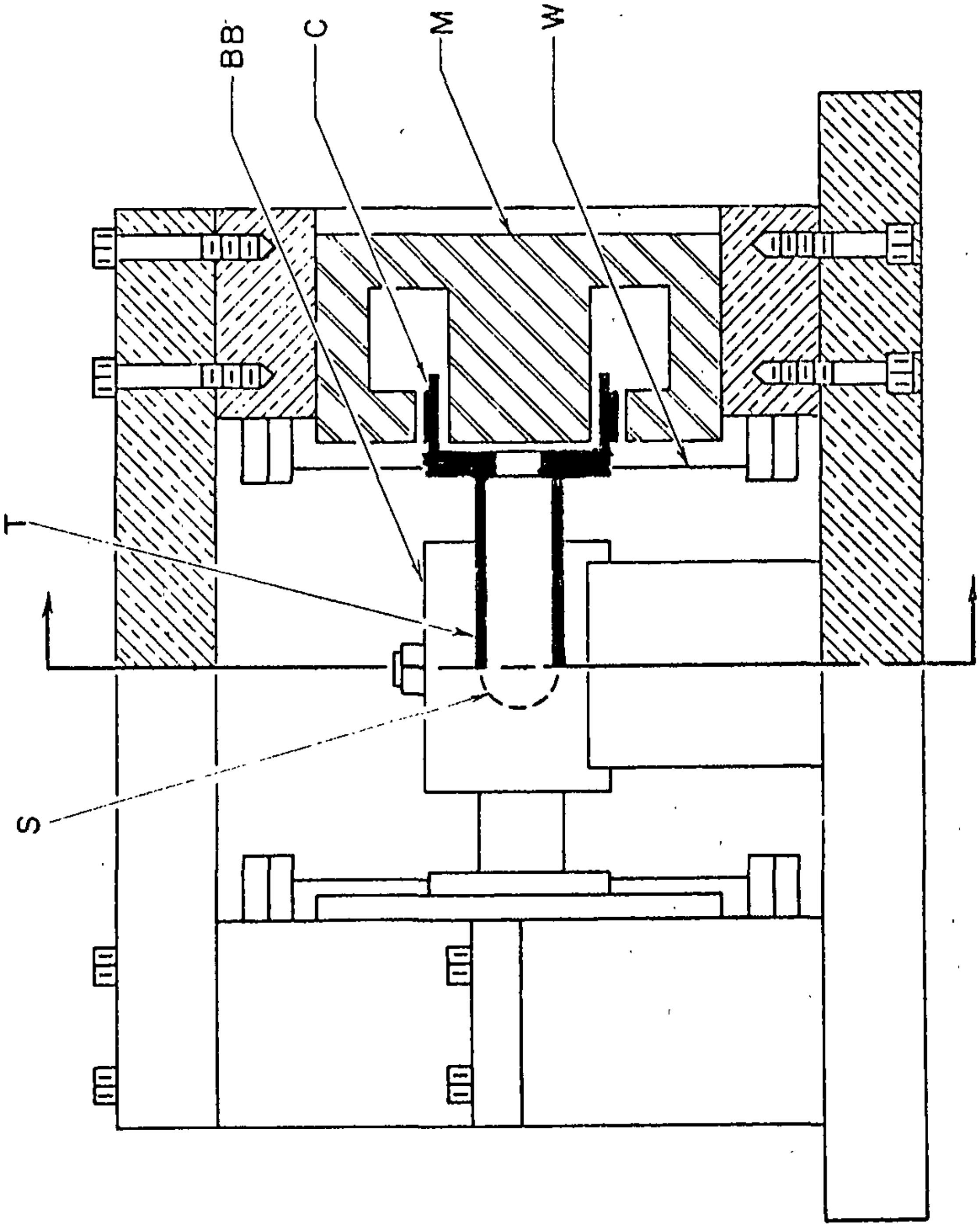


Figure 3

blocks may be determined by using a micrometer depth gage and determining the position of the outer face of the block. The heavy plate across the top of the instrument is important since it eliminates vibration of the magnets which occur in the frequency range of 200 to 300 c.p.s. Temperature control is maintained by thermostating the instrument in a side port bath which was constructed to house the instrument. The bath temperature is controlled to 0.1°C. and fluctuations in sample temperature are probably less than ± 0.05°C. Cooling is provided by means of a Lehigh refrigeration unit (11).

Theory and Operation

If an alternating current $\vec{I_1}$ is supplied to coil 1, Figure 4, the resulting force on the tube will be given by

$$\vec{F} = B_1 \vec{I_1} \ell_1 \tag{11}$$

where B_1 is the flux density at coil 1 and ℓ_1 is the length of the wire. As a result of this sinusoidal force the tube will oscillate with instantaneous velocity,

$$\vec{V} = \frac{\vec{F}}{\vec{Z}_m} \tag{12}$$

where $\vec{Z}_m$ is the mechanical impedance of the tube. An open circuit voltage,

$$\vec{E_2} = B_2 \ell_2 \vec{v} \tag{13}$$

will be induced in coil 2. The mechanical impedance of the double transducer is therefore given by

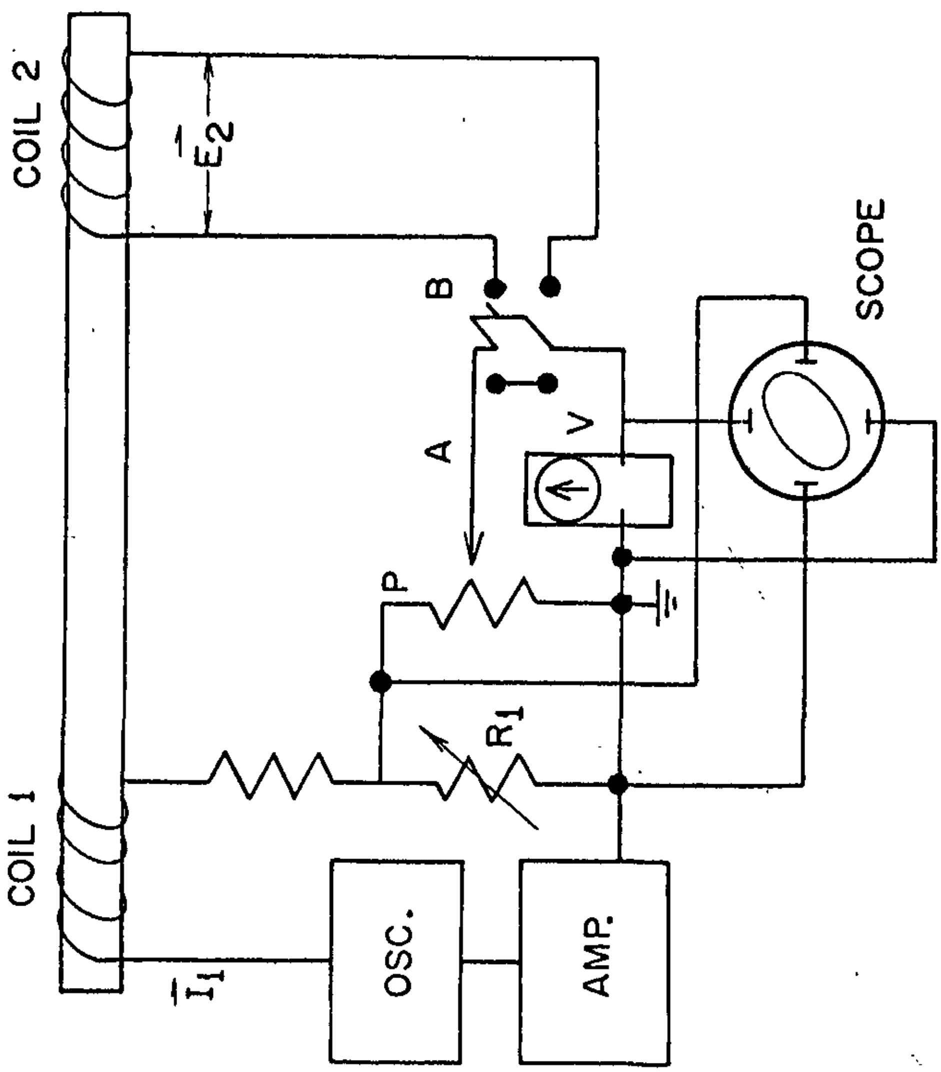


Figure 4. Circuit Diagram for the Electromagnetic Transducer

$$\vec{Z}_m = \vec{F} / \vec{v} = (B_1 \ell_1)(B_2 \ell_2) \vec{I}_1 / \vec{E}_2 \tag{14}$$

This is a fundamental expression for a double transducer. The ratio of $\vec{I}_1 / \vec{E}_2$ is known as the electrical transfer admittance. Equation (14) can be rewritten in terms of an instrument constant, K^2, as,

$$\vec{Z}_m = K^2 \vec{I}_1 / \vec{E}_2 \quad , \tag{15}$$

where $K^2 = (B_1 \ell_1)\ (B_2 \ell_2)$. According to equation 15, the measurement of mechanical impedance of a double transducer is reduced to a measurement of electrical transfer admittance. The derivation of this equation assumes that the transducer tube behaves as a rigid rod and has no mechanical resonances.

If $\vec{Z}_{mo}$ represents the mechanical impedance of the transducer tube, and $\vec{Z}_m$ the impedance of the tube when shearing a sample, then the sample impedance will be given by

$$\vec{Z}_{ms} = \vec{Z}_m - \vec{Z}_{mo} \tag{16}$$

The complex shear modulus $G^* (j\omega)$, of the sample may now be calculated from the dimensions of the sample and the measured impedance in accordance with the equation,

$$G^* (j\omega) = j\omega \vec{Z}_{ms} [h / A] \tag{17}$$

where <u>h</u> is the thickness of the sample and <u>A</u> its area.

Electrical Measuring Circuits

According to Equation (15), the impedance of the tube may be determined by measuring the electrical transfer admittance $\vec{I}_1/\vec{E}_2$. This is accomplished by using the simple circuit shown in Figure 4. With the exception of the oscilloscope this is the circuit used by Marvin, Fitzgerald, and Ferry (12). The power for the driving coil, No. 1, is supplied by means of a Hewlett-Packard model 200 J audio oscillator (13) and is amplified by means of a McIntosh model MC-30, 30-watt power amplifier (14). Resistance R_1 is a 100 Ω General Radio type 1432 decade resistor (15). The potential divider P is an Electro-Measurements Dekavider model DV-411 (16) and the voltmeter V, is a Ballantine model 300 vacuum tube voltmeter (17). A Du Mont model 304-A oscilloscope is used as a visual phase detection device (18).

The real and imaginary components of the transfer admittance may be determined as follows.

With the switch in position B, the voltmeter will indicate a voltage, E_m, given by

$$E_m = \left[(\alpha_1 I_1 R_1 - E_{2_r})^2 + E_{2_i}^2 \right]^{1/2} , \tag{18}$$

where α_1, is a fraction of the potential drop I_1R_1 across the resistor R_1, E_{2_r} and E_{2_i} are the real and imaginary components of the voltage induced in coil 2. A value of α is observed such that

$$\alpha_1 I_1 R_1 = E_{2_r} . \tag{19}$$

Under these conditions the meter reading is simply, $E_m = E_{2_i}$. When this is true, E_m and I_1R_1 are perpendicular and the oscilloscope is arranged so as to indicate a circle. This is a convenient means of determing E_{2_r}. The voltmeter reading is carefully noted and the switch is set in position A and the potential divider is readjusted to a new value α_2 such that the previous voltmeter reading is reproduced. The new condition is now,

$$\alpha_2 I_1R_1 = E_{2_i}. \tag{20}$$

The function of the voltmeter in these two steps is that of a null point instrument.

By substituting the relation

$$(E_2)^2 = (E_{2_r})^2 + (E_{2_i})^2 \quad , \tag{21}$$

along with Equations (19) and (20) into the fundamental transducer relation (15) we obtain,

$$\vec{Z}_m = (K^2/R_1) [\alpha_1/(\alpha_1^2 + \alpha_2^2)] + j(K^2/R_1) [\alpha_2/(\alpha_1^2 + \alpha_2^2)] . \tag{22}$$

By setting, $A_1 = \alpha_1/(\alpha_1^2 + \alpha_2^2)$ and $A_2 = \alpha_2/(\alpha_1^2 + \alpha_2^2)$ this becomes,

$$\vec{Z}_m = (K^2/R_1) A_1 + j(K^2/R_1) A_2. \tag{23}$$

According to this relation, the complex mechanical impedance can be determined by means of simple potential divider settings and a knowledge of K^2

and R, both of which are known or can be determined.

Transducer Calibration

Consider the tube without a sample. If m is the mass of the transducer tube, k is the elastance of the supporting wires and if f is a viscous factor due to air resistance, etc., Equation (23) becomes,

$$\vec{Z}_{mo} = \frac{K^2}{R_1} A_{10} + j\frac{K^2}{R_1} A_{20} \qquad (24)$$

and

$$f + j(\omega m - \frac{k}{\omega}) = \frac{K^2}{R_1} A_{10} + j\frac{K^2}{R_1} A_{20} \qquad (25)$$

where the subscript (0) refers to the unloaded tube. There will be a resonance when the imaginary part of the expression vanishes. For the present instrument this is found at 12 c.p.s. At frequencies well above this resonance, $\frac{k}{\omega}$ becomes small and since f is also very small, we obtain the approximation,

$$A_{20} = \frac{mR}{K^2}\,\omega\ . \qquad (26)$$

A plot of A_{20} vs. frequency, ν, should give a straight line of slope $2\pi m R_1/K^2$. Since m is known, K^2 may be calculated. A typical calibration curve is shown in Figure 5. The straight line up to 1700 c.p.s. is an indication that no electrical or mechanical resonances are present. The value of K^2 determined from this line is, $K^2 = (1.061 \pm 0.015) \times 10^4$ ohm dyne sec. cm.$^{-1}$.

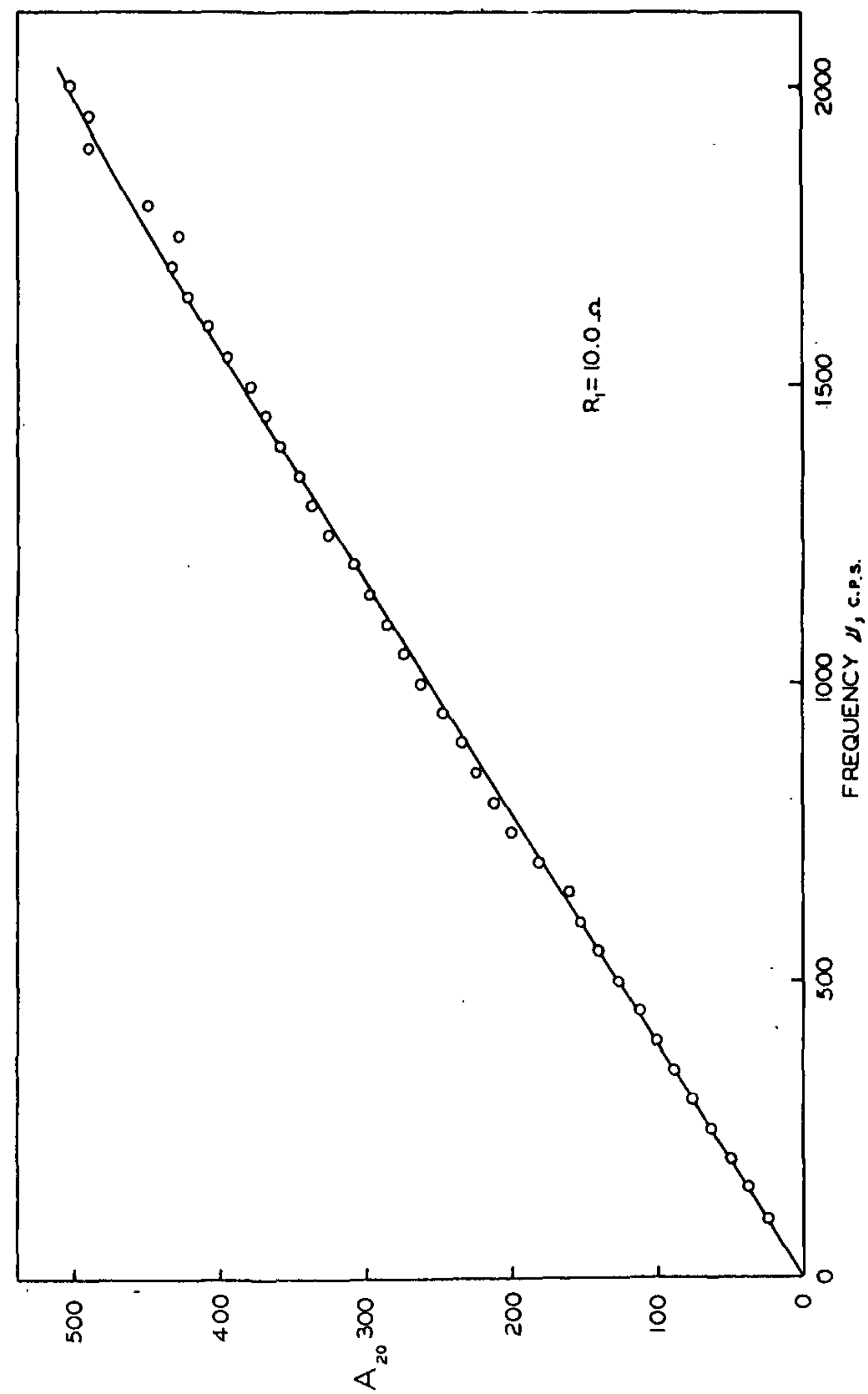


Figure 5. Calibration Curve for the Electromagnetic Transducer with R_1 = 10.0 ohm

An alternate procedure, which illustrates the important mechanical resonances of the tube, is to plot log A_{20} against log ω and as long as the tube is behaving as a rigid rod, a straight line with a slope of unity will be observed. Such a plot is shown in Figure 6 indicating resonances at both low and high frequencies. The low frequency resonance has already been discussed. The resonance at high frequencies is due to the fact that the tube is no longer acting as a rigid rod. This resonance is above 6,000 c.p.s. and is due to the first transverse vibrational mode of the tube.

The real component of Equation 24 can be written as

$$A_{10} = f \frac{R}{K^2} \tag{27}$$

and represents the friction of the tube. This component decreases rapidly with increasing frequency and should become zero at high frequencies. Actually, numerical values of A_{10} become too small to measure between 100 and 700 c.p.s. and change sign above 700 c.p.s. so that measurements of this component cannot be made. This means that measurements above 700 c.p.s. should be made with caution as anomalous results can be obtained.

The inability to obtain measurements of A_{10} above 700 c.p.s. is due to a phase shift within the amplifiers of the oscilloscope which is used as a phase detection device. In principle it should be possible to obtain corrections for A_{10} by means of a suitable calibration. A calibration technique has been worked out but has not been tested sufficiently to report at the present time.

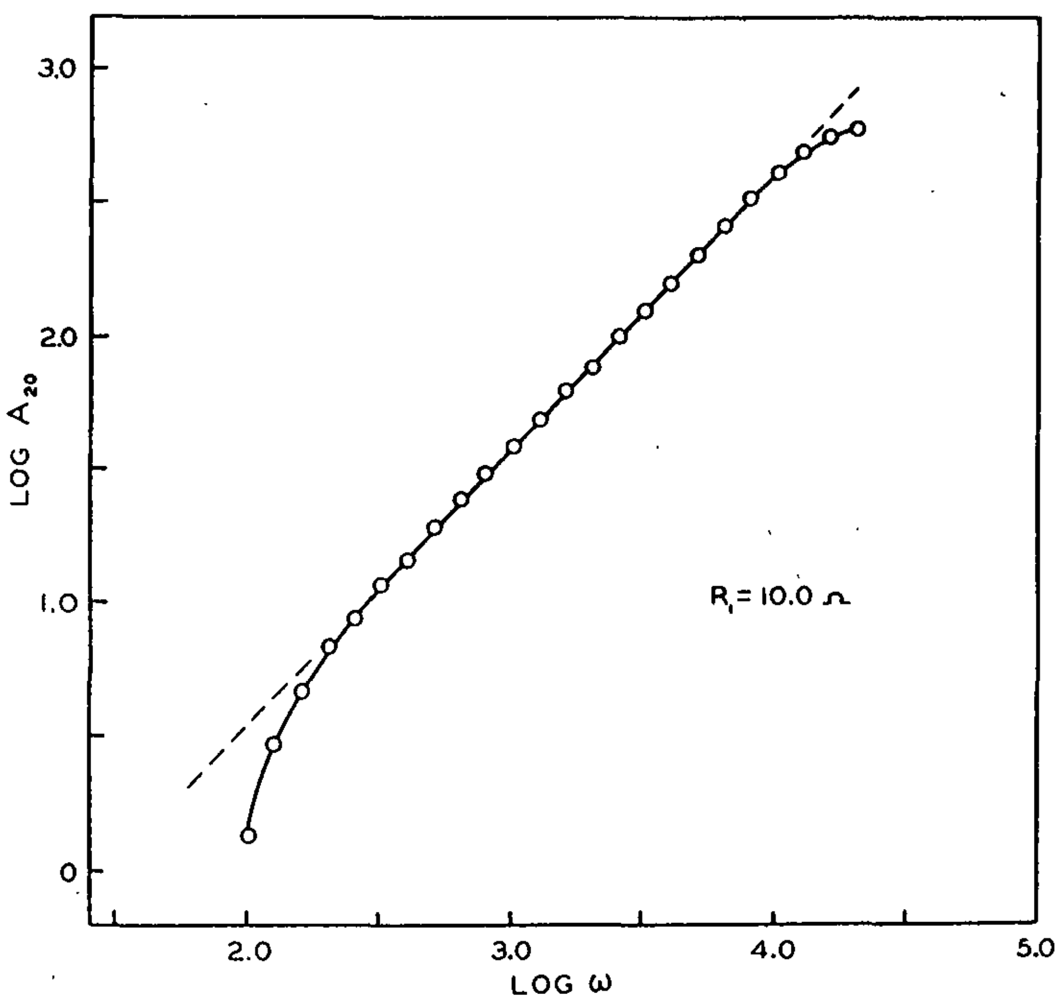


Figure 6. Calibration Curve for the Electromagnetic Transducer Showing Major Mechanical Resonances

II. PRELIMINARY INVESTIGATIONS ON THE DYNAMIC MECHANICAL PROPERTIES OF MATERIALS OF INTEREST TO THE PAPER INDUSTRY

INTRODUCTION

There are a number of papermaking materials which might be profitably investigated using the electromagnetic transducer. The materials in this preliminary investigation were chosen because they represent materials which differ widely in their mechanical properties and in the dependence of the mechanical properties on frequency. The materials selected for this investigation are:

A. Films cast from butyl latex.

B. Wet pulp mats.

C. Miscellaneous materials; gels of cellulose acetate in triethyl citrate, a tack-graded black printing ink, and pigment loaded elastomers.

DYNAMIC MECHANICAL PROPERTIES OF FILMS CAST FROM BUTYL RUBBER LATEX

A large number of paper coatings are formulated using elastomeric substances. Natural rubber and natural rubber derivatives, neoprene, butyl rubber, and butadiene-polystyrene latices are a few of the elastomers that have been used in coating. These materials are ideally suited for electromagnetic transducer measurements and a great deal of practical information can be obtained. Butyl rubber latex is typical of the latices used in coating and has been selected to illustrate the use of the transducer.

Experimental Procedures and Results

The elastomer used in the following experiments was a sample of butyl rubber latex, ID-600-47, obtained from the Esso Research and Engineering Company of Lindon, New Jersey. It has a solids content of 47%. A film of latex was cast on a glass plate and allowed to dry for a period of 48 hours at 73°F. and a relative humidity of 50%. The films were stripped from the glass plate and cut into squares for transducer measurement.

Real and imaginary components of the complex shear modulus were measured as a function of frequency and temperature. The frequency range covered was 6 to 800 c.p.s. and measurements were taken at 0.2, 10.2, 15.0, 19.8, 24.4, 30.0, and 34.6°C. Both components of the complex shear modulus were treated according to the meathod of reduced variables (19) through the use of the relations,

$$G_r'(\omega) = G'(\omega)\,\frac{T_o\rho_o}{T\rho} \qquad (28)$$

and

$$G_r''(\omega) = G''(\omega)\,\frac{T_o\rho_o}{T\rho}\,, \qquad (29)$$

where $G_r'(\omega)$ and $G_r''(\omega)$ are the real and imaginary components of the reduced complex shear modulus, T is the temperature and ρ is the density. The thermal expansion coefficient of butyl rubber was taken to be 4×10^{-4} deg.$^{-1}$. Real and imaginary components of the reduced complex shear modulus are shown in Figures 7 and 8 and are reduced to an arbitrary reference temperature of 24.4°C.

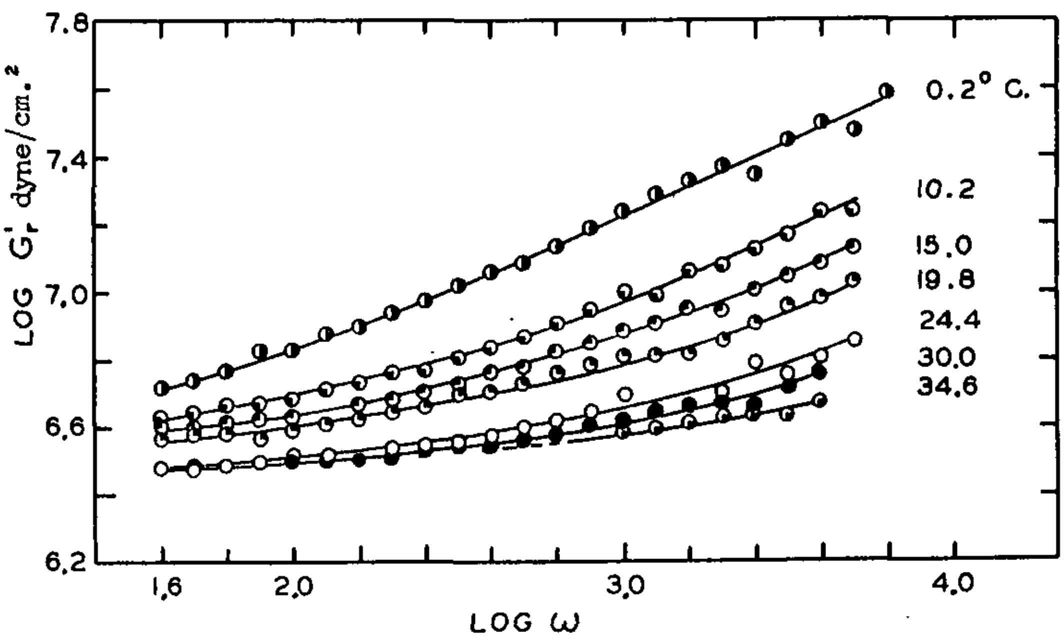


Figure 7. Real Component of the Reduced Complex Shear Modulus in dyne/cm.² for Butyl Rubber

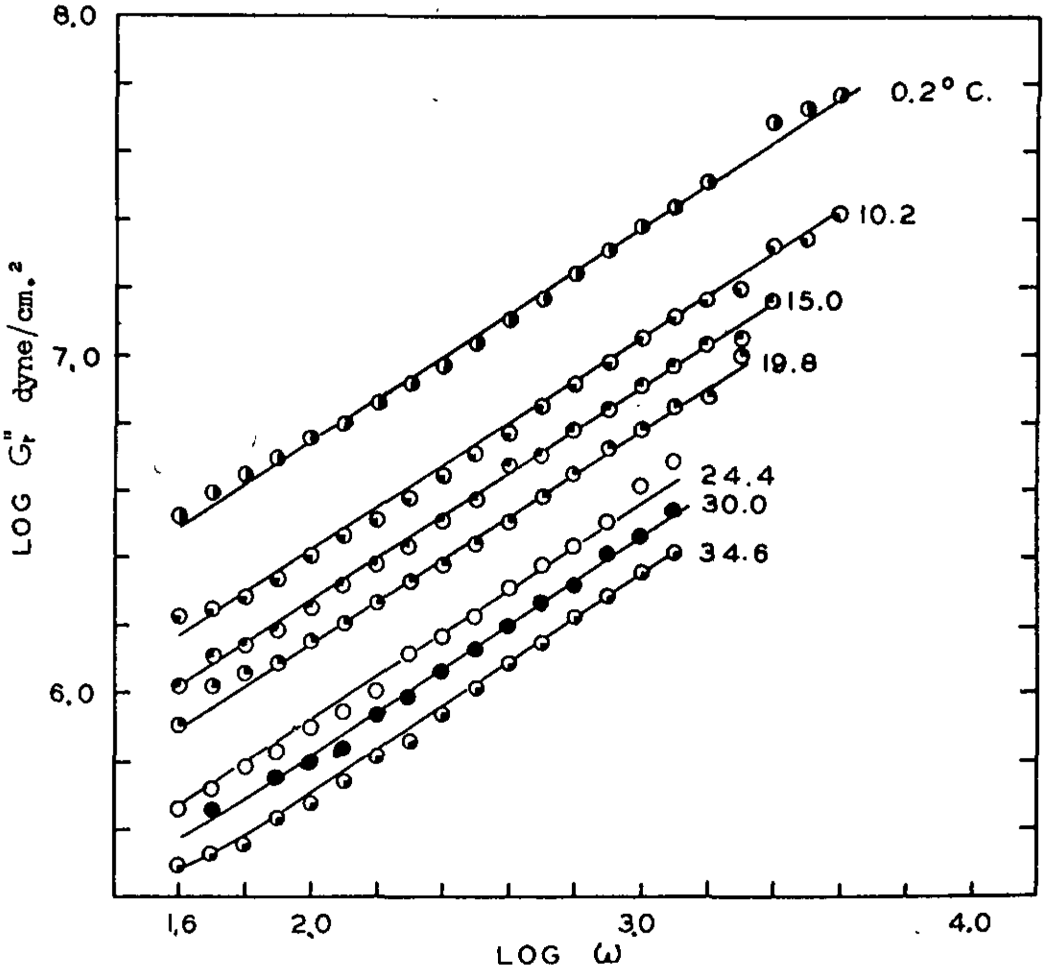


Figure 8. Imaginary Component of the Reduced Complex Shear Modulus in dyne/cm.² for Butyl Rubber

To complete the reduction, master curves can be constructed by multiplying all frequencies at a given temperature by a reduction factor, a_T. The a_T factors are a function of temperature but are the same for both real and imaginary components at a given temperature. The master reduced curves of Figure 9 were obtained using this method. The curves at 24.4°C. were chosen as reference and all curves have been made to coincide with the reference. The corresponding reduction factors are given in Table II.

TABLE II

REDUCTION FACTORS FOR BUTYL RUBBER

Reference Temperature = 24.4°C

Temperature, °C.	Reduction Factors, $\log a_T$
34.6	-0.35
30.0	-0.17
24.4	0
19.8	+0.33
15.0	+0.54
10.2	+0.78
0.2	+1.30

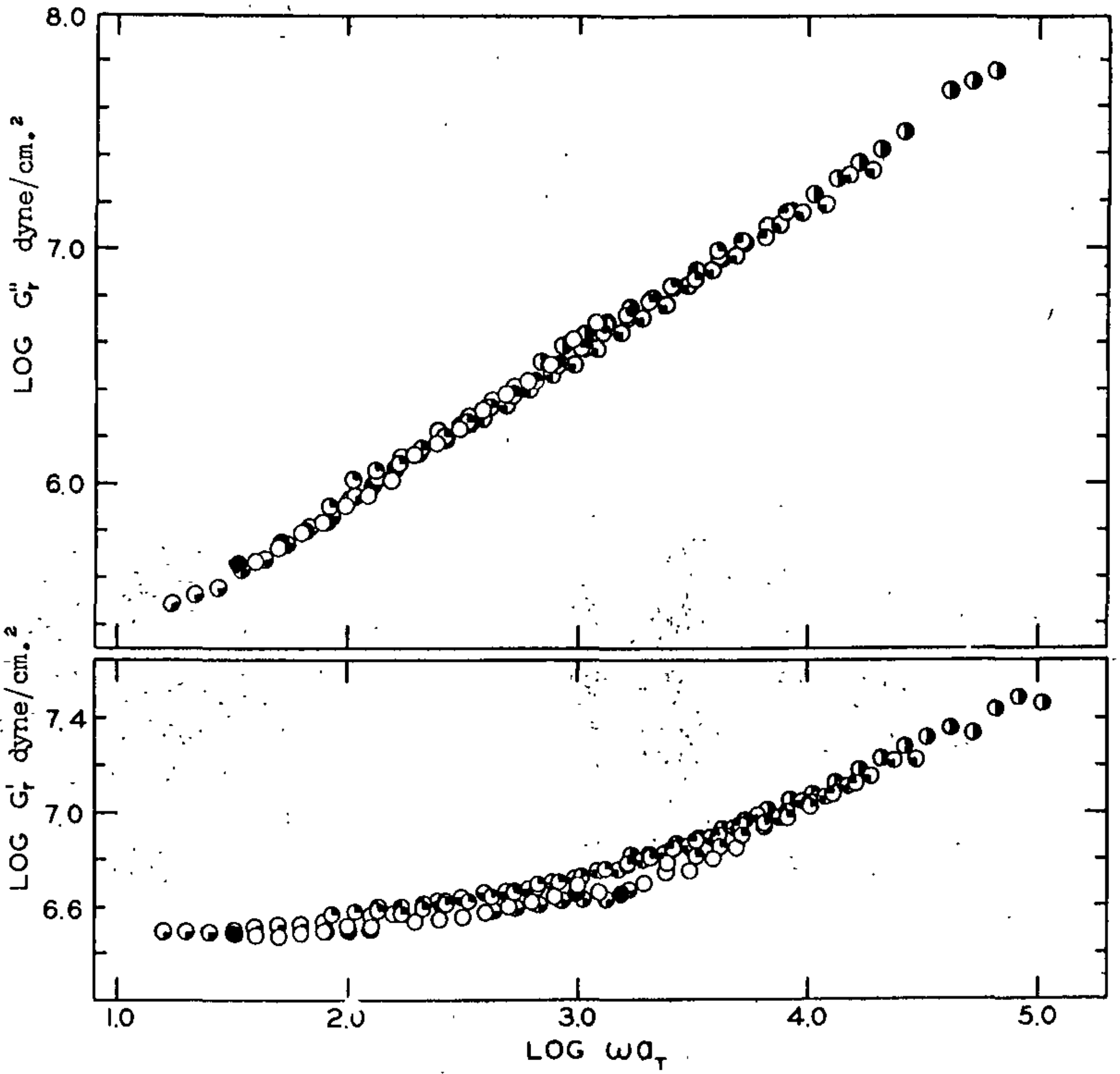


Figure 9. Real and Imaginary Components of the Complex Shear Modulus in dyne/cm.² for Butyl Rubber, Reference Temperature, 24.4°C.

The Temperature Dependence of the Reduction Factor

For many polymers and organic and inorganic glass forming liquids the reduction factors can be made to conform to a single composite curve (20). This generalization can be expressed as (21)

$$\log a_T = -C_1(T - Tg)/(C_2 + T - Tg), \qquad (30)$$

where Tg is the glass transition temperature. The coefficients C_1 and C_2 are approximately universal constants. These constants are related to the fractional free volume ϕg at the glass transition temperature and its thermal expansion coefficient α' by the relations $\phi g = 1/2.303C_1$ and $\alpha' = \phi g/C_2$. For many polymer systems $C_1 = 17.44$ and $C_2 = 51.6$ (which correspond to $\phi g = 0.025$ and $\alpha' = 4.8 \times 10^{-4}$ deg.$^{-1}$).

The reduction factors of Table II can be made to satisfy Equation (30). This relation is extremely important since it establishes the temperature dependence of mechanical properties with respect to the glass transition temperature and, hence, to a critical point for the glassy state.

DYNAMIC MECHANICAL PROPERTIES OF WET PULP MATS

At the present time there appears to be no published measurements on the dynamic mechanical properties of wet pulp mats. Measurements on the dynamic Youngs' modulus of paper have been reported in the 20 to 100 c.p.s. frequency range using a vibrating reed technique (22). The flexural rigidity of paper has been measured in this laboratory (23) using torsion pendulum and flexural vibration methods. These methods are essentially resonance methods and as such are generally limited to a few fixed frequencies or to a limited frequency range. In addition, the imaginary component of the modulus is usually masked by the effect of air friction on the sample and, therefore, can not be measured.

The electromagnetic transducer has the advantage of covering a wide range of frequencies continuously and can be used on materials of low rigidity. Both real and imaginary components of the complex shear modulus can be determined even though the imaginary component is small compared to the real component.

Experimental

The pulp used in this preliminary investigation was a sample of Weyerhaeuser bleached sulfite pulp beaten to a Schopper-Riegler freeness of 725 cc. Pertinent physical test data are given in the appendix.

Samples were prepared by forming a thick mat on a sheet mold using a high consistency slurry. Sample pairs were then cut from the mats using a razor blade. The area of each sample was approximately 4.09 cm^2. In preparing samples, extreme care was taken to avoid excessive mechanical working since this was known to have a considerable effect on the magnitude of the complex shear modulus. The samples were always maintained in a wet condition. When possible they were immersed in water.

Real and imaginary components of the complex shear modulus were studied as a function of frequency and sample thickness since the design of the transducer is such that samples can be compressed to any desired thickness. The results of one series of experiments are shown in Figure 10

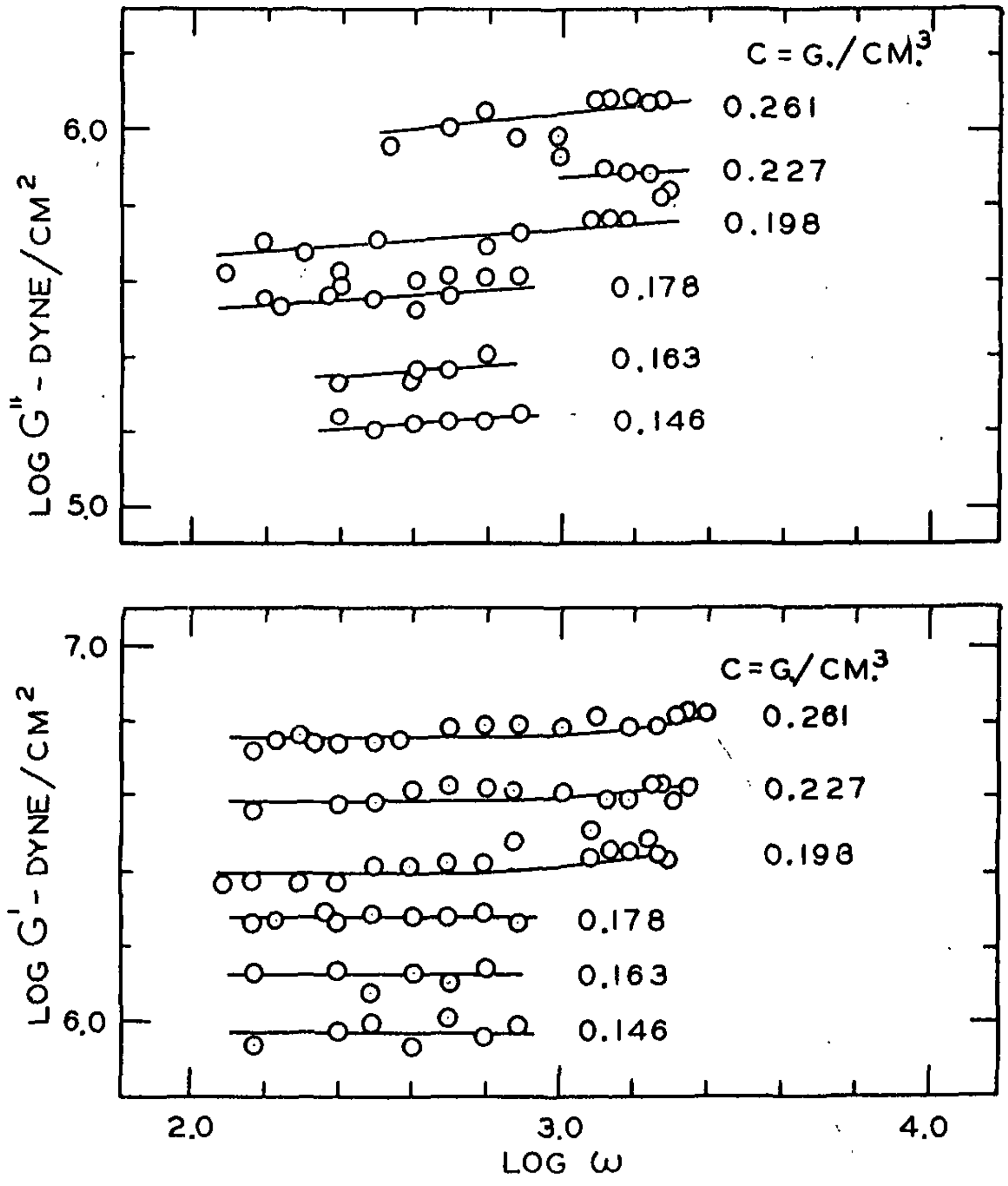


Figure 10. Real and Imaginary Components of the Complex Shear Modulus for Weyerhaeuser Bleached Sulfite Pulp at Various Pad Concentrations

where real and imaginary components of the complex shear modulus are shown. The pad concentration, C = g./cm.^{3}, was computed from a knowledge of sample dimensions and the dry weight of the pad. Pad concentration is based on the weight of the dry fiber. The complex shear modulus was computed solely on the basis of wet sample dimensions and is, therefore, an apparent modulus.

There is relatively little change in the two components of the complex shear modulus within the frequency range studied (approximately 25 to 250 c.p.s.). The effect of compression upon the components of the modulus is rather interesting. First of all, compression appears to have no effect upon the frequency behavior. A possible explanation is that compression alters only the number of fiber to fiber contacts without causing marked changes in the fibers themselves. That is, the inherent flexibility of the individual fiber is not being altered through deformation. If deformation were altering the inherent flexibility of the individual fibers, one could expect that the imaginary component of the shear modulus would change with compression in a different manner than that of the real component. Actually, both the real and imaginary components have the same percentage increase upon compression and the mechanical loss tangent is independent of compression. This also indicates that the viscous flow of water past individual fibers has no effect on the mechanical properties we are measuring. If viscous flow of the water were important it would be observed as a viscous contribution to the imaginary component of the complex shear modulus. The imaginary component would, therefore, be expected to have a different dependence on compression than that of the real component. This, however, is not the case.

There is an interesting relation between the components of complex shear modulus and the pad concentration. This is illustrated in Figure 11 where a linear relation is observed between the log G' or log G" and log C. Both components of the modulus can be fitted to an equation of the form

$$N \log G + \log M = \log C \tag{31}$$

where N and M are constants. Values of the constants are given in Table III.

TABLE III

CONSTANTS FOR THE RELATION N log G + log M = log C
FOR WEYERHAEUSER BLEACHED SULFITE PULP
AT A FREQUENCY OF 100 c.p.s.

Component	M	N
G'	0.00380	0.326
G"	.0‸00700	0.326

The data in Figure 11 as well as the constants in Table III are reported at an arbitrary frequency of 100 c.p.s. The relationship represented by Equation (31) has been found to hold for transducer measurements on at least one other pulp and appears to be valid over a 100-fold change in dynamic shear modulus. It also appears to be valid for both beaten and unbeaten pulp. A thorough investigation of this behavior is in progress at the present time.

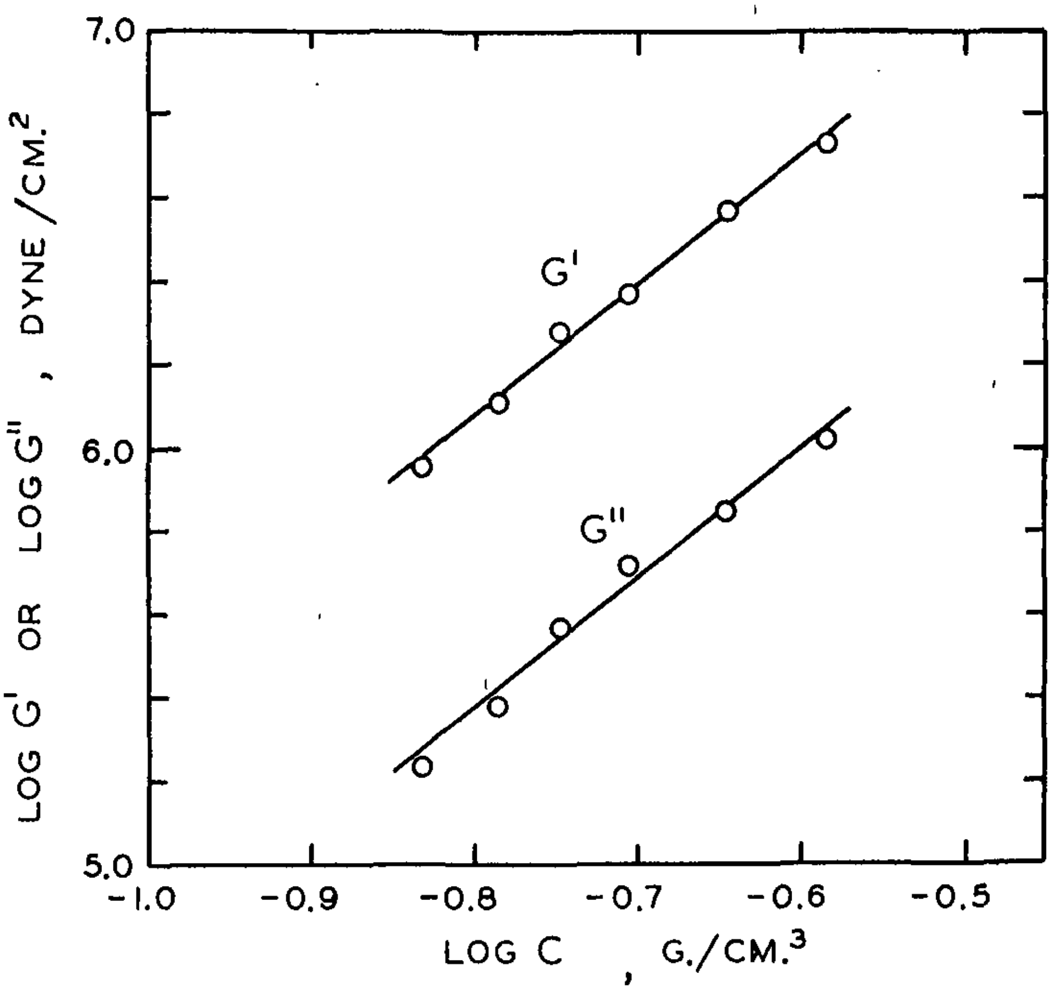


Figure 11. Real and Imaginary Components of the Complex Shear Modulus, at 100 c.p.s., as a Function of Pad Concentration. Weyerhaeuser Bleached Sulfite Pulp.

MISCELLANEOUS MATERIALS

The mechanical properties of several other materials were investigated in lesser detail. A gel of 71.6% triethyl citrate and 28.4% cellulose acetate (degree of substitution, 2.2) was prepared by heating at 100°C. for a period of 30 hours. Samples cast from this gel were of a rubbery nature and were subject to transducer measurement. The log plots of G' and G'' were found to be linear functions of log ω from 6.3 to 600 c.p.s. The variation of these components with temperatures between 25°C. and 0°C. was studied. The real and imaginary components of the complex shear modulus were found to depend on thermal history although the slope of the log G' and log G'' vs. log ω curves remained unaffected by temperature. A similar frequency behavior has been observed for nitrocellulose gels (24). This is a peculiar frequency behavior and warrants further investigation since it may be a property of the stiff backbone chain attributed to the cellulose molecule and as such may provide a means of evaluating many other mechanical properties of cellulose derivatives in terms of this stiffness.

A brief series of tests were performed on one sample of a tack-graded black printing ink standard consisting of mineral oil and a carbon black. The ink was of a butter-like consistency at room temperature. Drops of ink were placed on the sample blocks of the transducer and were then pressed into thin films approximately 0.010 inch. The absolute value of the complex shear modulus could not be measured with reliability. However, values relative to a given frequency of 6.3 c.p.s. were easy to obtain.

As might be expected, the real component of the complex shear modulus was too small to measure and the dynamic viscosity was virtually independent of frequency from 6.3 to 600 c.p.s.

Pigment loaded elastomers represent a final class of materials that can be studied by means of the transducer. Butyl rubber with a clay content as high as 80% can be prepared in the form of thin films. Samples suitable for transducer measurement can be cut from these films. The frequency behavior of the dynamic shear modulus, the dynamic viscosity, and the mechanical loss tangent can be determined with ease. This is, therefore, a convenient and fundamental means of studying the mechanical properties of films used in paper coatings.

APPENDIX

PHYSICAL DATA FOR WEYERHAEUSER BLEACHED SULFITE PULP
AT 50% RELATIVE HUMIDITY AND 73°F.

Schopper-Riegler freeness, cc.	725
Basis weight, lb./25 x 40 x 500	45.7
Caliper, mils	4.0
Bursting strength, Mullen	37.5
Burst, pts./100 lb.	81
Elmendorf tear, g./sheet	44
Tear factor	0.96
Schopper tensile, lb./in.	19.9
Gurley porosity, sec./100 cc.	122
Zero span tensile, lb./in.	40.6
Instron tensile, lb./in.	19.5
Instron stretch, %	2.8

NOMENCLATURE

α = potential divider settings

α' = coefficient of thermal expansion of free volume

ϵ = strain

η' = dynamic viscosity

ν = frequency, c.p.s.

ρ = density

σ = stress

τ = relaxation time

ϕ = fractional free volume

ω = circular frequency, $2\pi\nu$

$\tan\delta$ = $G''(\omega)/G'(\omega)$ = $J''(\omega)J'(\omega)$ = mechanical loss tangent

a_T = reduction factor

f = frictional resistance of transducer tube

h = sample thickness

j = $\sqrt{-1}$

k = Spring constant, elastance of tube support wires

l = length of wire in transducer coils

m = mass of transducer tube

t = time

$\vec{v}$ = velocity

NOMENCLATURE, continued

A = sample area

$A_1 = \alpha_1/(\alpha_1^2 + \alpha_2^2)$

$A_2 = \alpha_2/(\alpha_1^2 + \alpha_2^2)$

B = magnetic flux density

C = capacitance, also coefficient for Williams, Landel, and Ferry equation, and pad concentration

E = voltage

E_{2_r}, E_{2_i} = real and imaginary components of voltage induced in coil 2.

$\vec{F}$ = force

$G_1^*(j\omega)$ = complex shear modulus, dyne/cm.^{2}

$G'(\omega)$ or G' = real component of complex shear modulus, dyne/cm.^{2}.

$G''(\omega)$ or G'' = imaginary component of complex shear modulus, dyne/cm.^{2}.

$H(\tau)$ = relaxation distribution function

$\vec{I}$ current

$J^*(\omega)$ = complex shear compliance, cm.^{2}/dyne

$J'(\omega)$ or J' = real component of the complex shear compliance, cm.^{2}/dyne

$J''(\omega)$ or J'' = imaginary component of the complex shear compliance, cm.^{2}/dyne

$K^2 = (B_1 l_1)(B_2 l_2)$ = transducer constant ohm dyne sec. cm.$^{-1}$

L = inductance

R = resistance

T = temperature

Tg = glass transition temperature

$\vec{Z}$ = impedance

NOMENCLATURE, continued

$\vec{Z}_e$ = electrical impedance

$\vec{Z}_m$ = mechanical impedance

$\vec{Z}_{mo}$ = mechanical impedance of unloaded transducer tube

$\vec{Z}_m$ = mechanical impedance of loaded transducer tube when shearing a sample

$\vec{Z}_{ms}$ = mechanical impedance of the sample

REFERENCES CITED

1. Passaglia, E., and Kurath, S. F. Unpublished work, 1955.

2. The author of this report is indebted to Mr. M. Filz and Mr. L. Dambruch, respectively, for constructingand procuring materials for the transducer.

3. Ferry, J. D., and Williams, M. L. J. Colloid Sci. 7;347(1952).

4. The tube was milled from Alcoa 6063-TS aluminum, extruded square tubing having sharp corners, 1 by 0.125-inch walls, and is available at Steel Sales Corporation, Appleton, Wisconsin.

5. Dow metal alloy FS-1-H-24, Dow Chemical Company, Chicago, Illinois.

6. Constructed from No. 52 Westinghouse Micarta tubing, 1/32-inch wall by 1-1/2-inch I.D. This is available at Westinghouse Electric Corporation, Appleton, Wisconsin.

7. Magnet wire, No. 34, Anaconda orange coated wire. Available at Kurz Electric Company, Appleton, Wisconsin. The wire is attached to the coil forms with an insulating and dipping varnish obtained from the General Cement Manufacturing Company, Rockford, Illinois.

8. Cast Alnico 5-ring magnet with the direction of magnetization parallel to the length and having a ground finish. The dimensions are 4.101 O.D. x 2.994 I.D. x 2 in. length. This was obtained from the Permag Corporation, 214 Taaffe Place, Brooklyn 5, New York.

9. Magnetic (Armco ingot iron) hot-rolled round, 4-inch diameter, in an annealed condition from the Steel Sales Corporation, 2400 W. Cornell Street, Milwaukee, Wisconsin.

10. The magnet holders were machined from a 3 by 30-inch square brass rod, free cutting, from Central Steel & Wire Company, 6623 W. Mitchell Street, Milwuakee 14, Wisconsin. The top and base of the instrument were machined from hot-rolled Muntz metal sheet from the Fullerton Metal of Wisconsin, Inc., 3400 S. Hanson Street, Milwaukee 7, Wisconsin.

11. Lehigh model AM42-FE-46 refrigeration unit, Lehigh Mfg. Co., Lancaster, Pennsylvania.

12. Marvin, R. S., Fitzgerald, E. F., and Ferry, J. D. J. Appl. Phys. 21: 197(1950).

13. Hewlett-Packard Company, Palo Alto, California

14. McIntosh model MC-30, 30 watt power amplifier, Type A-116B, Serial 15329 and over. McIntosh Laboratory, Inc., 2 Chambers Street, Binghamton, New Jersey.

15. General Radio Company, Cambridge 39, Massachusetts.

16. Electro Measurements, Inc., Portland, Oregon.

17. Ballantine Laboratories, Inc., Boonton, New Jersey.

18. A. B. Du Mont Laboratories, Clifton, New Jersey.

19. Ferry, J. D., et al., J. Appl. Phys. 22:717(1951).

20. Williams, M. L. J. Phys. Chem. 59:95(1955).

21. Williams, M. L., Landel, R. F., and Ferry, J. P. J. Am. Chem. Soc. 77:3701(1955).

22. Horio, M., and Onogi, S. J. Appl. Phys. 22:971(1951).

23. Nethercut, P. E. A fundamental study of the softening mechanism of paper plasticizers. Doctor's Dissertation. Appleton, Wis., The Institute of Paper Chemistry, 1949.

24. Plazek, D. J. Doctor's Dissertation. Madison, Wis., The University of Wisconsin, 1957.

MAY 27 1965

(1) Proposal No: ______

Letter Date: ______

Modifications: ______

Signed by: ______

Supervisor(s): √Swanson

Rejected: ______

(6) Co-operators:

THE INSTITUTE OF PAPER CHEMISTRY

(7) Inst. X Member ___ Allied ___ Group ___

Project No. 2045

Page 1 date 10/14/57

Change in Section: ______

Authorization of Co-operator: OK per J. G. Strange

IPC Approval: WHS (by) 10/14/57 (date)

(8) Project CLOSED date: MAY 24 1965

(2) TITLE: DOUBLE ELECTROMAGNETIC TRANSDUCER

(3) BUDGET:

Approx. $600 for new equipment
Approx 900 for labor to construct
and also approx $700 in equipment already available at IPC

(4) TIME SCHEDULE:

(9) BRIEF SCOPE OF PROJECT:

Refer to memorandum of September 11, 1957 by Dr. S. Kurath to John Swanson. This project would be concerned with the construction of a double electromagnetic transducer and application of this instrument to various problems involving the mechanical properties of polymers of interest to the paper industry.

(5) ADMIN. COPIES:

__Becker
__Boya
__Garrett
__Laughlin
__Smith(5)
__Strange
__Wadsworth
__Supervisor
__Central File

PLAIN COPIES TO:

__Browning	__Kregel	__Swanson
__Buchanan	__Kremers	__Theisen
__Dickey	__Lewis	__V.d.Akker
__Green	__May	__Van Horn
__Hamilton	__McKee	__Ward
__Howells	__McLeod	__Weiner
__Ingmanson	__Pearl	__Whitney
__Isenberg	__Rae	__Wink
__Joranson	__Sears	__Wise
__Brown		__Zastrow

(10) Remarks:

Form No. 7-2a
10/56-450

RESEARCH ORDER
Confidential

roject [illegible]ports			Progress Reports		Invoices			Miscellaneous
o	Date	By	No.	Date	Date	Amount	Subtotal	
	6-30-58	Kurath	~~1~~	~~6-30-58 Kurath~~				
								2/28/58 transducer computation sheets being crossed referenced to Research notebooks & stored in vault.